DOCUMENT RESUME

ED 114 089 IR 002 718

AUTHOR Collins, Allan; Grignetti, Mario C.

TITLE Intelligent CAI. Final Report (1 March 1971-31 August 1975).

INSTITUTION Bolt, Beranek and Newman, Inc., Cambridge, Mass.

SPONS AGENCY Office of Naval Research, Washington, D.C. Personnel and Training Research Programs Office.
REPORT NO BBN-R-3181
PUB DATE Oct 75
NOTE 56p.

EDRS PRICE MF-$0.76 HC-$3.32 Plus Postage
DESCRIPTORS *Computer Assisted Instruction; Computer Oriented Programs; Computer Programs; *Educational Technology; Individualized Instruction; Programed Tutoring; State of the Art Reviews; Teaching Models; Tutorial Programs; *Tutoring
IDENTIFIERS *Intelligent CAI Systems; Map SCHOLAR; Natural Language Programing; NLS SCHOLAR; SCHOLAR; SOPHIE; Tutor SCHOLAR

ABSTRACT

Intelligent computer assisted instruction (CAI) systems are exemplified by several tutorial systems including Tutor-SCHOLAR, Map-SCHOLAR, NLS-SCHOLAR and SOPHIE. The original SCHOLAR program structure made it possible to model the way human tutors interact with students. Further analyses of tutoring and teaching strategies led to the development of Tutor-SCHOLAR. Intelligent computer systems illustrate how a variety of techniques can be used for tutoring visual knowledge, procedural knowledge, and diagnostic skills using natural language. (Author/CH)

****
* Documents acquired by ERIC include many informal unpublished *
* materials not available from other sources. ERIC makes every effort *
* to obtain the best copy available. Nevertheless, items of marginal *
* reproducibility are often encountered and this affects the quality *
* of the microfiche and hardcopy reproductions ERIC makes available *
* via the ERIC Document Reproduction Service (EDRS). EDRS is not *
* responsible for the quality of the original document. Reproductions *
* supplied by EDRS are the best that can be made from the original. *
****

ED114089

BOLT BERANEK AND NEWMAN INC

CONSULTING • DEVELOPMENT • RESEARCH

BBN Report No. 3181

IR

INTELLIGENT CAI

Final Report for Contract No. N00014-71-C-0228

Allan Collins
Mario C. Grignetti

October 1975

Sponsored by

Office of Naval Research and the
Advanced Research Projects Agency

Approved for public release; distribution unlimited.
Reproduction in whole or in part is permitted for
any purpose of the United States Government.

IR 008 718

Intelligent CAI

Allan Collins
Mario C. Grignetti

U.S. DEPARTMENT OF HEALTH, EDUCATION & WELFARE
NATIONAL INSTITUTE OF EDUCATION
THIS DOCUMENT HAS BEEN REPRODUCED EXACTLY AS RECEIVED FROM THE PERSON OR ORGANIZATION ORIGINATING IT. POINTS OF VIEW OR OPINIONS STATED DO NOT NECESSARILY REPRESENT OFFICIAL NATIONAL INSTITUTE OF EDUCATION POSITION OR POLICY

Bolt Beranek and Newman Inc.

Cambridge, Massachusetts 02138

Contract No. N00014-71-C-0228, dated March 1, 1971
Amendment Modification No. P00002, dated January 1, 1973
Expiration Date, June 30, 1975
Total Amount of Contract $586,000
Principal Investigator, Allan M. Collins [(617) 491-1850]

Sponsored by: Office of Naval Research
Contract Authority No. NR 154-330
Scientific Officers: Dr. Marshall Farr and
Dr. Joseph Young

and

Advanced Research Projects Agency
ARPA Order No. 2284, dated August 30, 1973
Program Code No. 61101E

The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the Advanced Research Projects Agency, the Office of Naval Research, or the U.S. Government.

Approved for public release; distribution unlimited. Reproduction in whole or in part is permitted for any purpose of the United States Government.

Unclassified
SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER Technical Report No. 6	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Intelligent CAI		5. TYPE OF REPORT & PERIOD COVERED Final Report (1 March 71-31 Aug. 75)
		6. PERFORMING ORG. REPORT NUMBER BBN Report No. 3181
7. AUTHOR(S) Allan Collins, Mario C. Grignetti		8. CONTRACT OR GRANT NUMBER(S) No. N00014-71-0228
9. PERFORMING ORGANIZATION NAME AND ADDRESS Bolt Beranek and Newman Inc. 50 Moulton Street, Cambridge, Mass.		10. PROGRAM ELEMENT PROJECT TASK AREA & WORK UNIT NUMBERS 61153N RR042-06;PR042-06-01 NR154-330
11. CONTROLLING OFFICE NAME AND ADDRESS Personnel and Training Research Programs Office of Naval Research (Code 458) Arlington, VA 22217		12. REPORT DATE October 1975 13. NUMBER OF PAGES 43
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Education, Tutoring, Computer-assisted instruction, Learning, Generative CAI, Teaching

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This paper describes the capabilities now available for building intelligent, tutorial CAI systems as exemplified by several systems including Tutor-SCHOLAR, Map-SCHOLAR, NLS-SCHOLAR and SOPHIE. The systems illustrate how a variety of sophisticated techniques can be used for tutoring different kinds of knowledge by carrying on dialogues in natural language. The systems have been developed to explore how to provide each student with his own personal, expert tutor.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

Unclassified
SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

Annotated Bibliography of Papers Prepared for this Project

Carbonell, J. R. and Collins, A. M. Natural semantics in artificial intelligence. In Proceedings of the Third International Joint Conference on Artificial Intelligence, Stanford University, 1973, 344-351. Reprinted in the American Journal of Computational Linguistics, 1, Mfc 3, 1974. (Partial support)

This paper discusses human semantic knowledge and processing in terms of the SCHOLAR system. In one major section we discuss the imprecision, the incompleteness, the open-endedness, and the uncertainty of people's knowledge. In the other major section we discuss strategies people use to make different types of deductive, negative, and functional inferences, and the way uncertainties combine in these inferences.

Collins, A. M., Passafiume, J. J., Gould, L., and Carbonell, J. G. Improving interactive capabilities in computer-assisted instruction. BBN Report No. 2631, 1973.

This report describes the development of interactive capabilities in the SCHOLAR CAI system centering in three main areas: (1) implementation of two presentation strategies in SCHOLAR (Tutorial mode and Block-Test mode) and a comparative evaluation of these two modes using high-school students as subjects; (2) initial study based on analysis of tutorial dialogues of how to teach

procedural knowledge interactively within SCHOLAR, and (3) addition of a module for teaching geography using the map display and related question-answering facilities recently added to SCHOLAR.

Collins, A. M., Warnock, E. H., and Passafiume, J. J. Analysis and synthesis of tutorial dialogues. In G. Bower (Ed.), The psychology of learning and motivation, Vol. 9. New York: Academic Press, 1975.

In this paper we attempt to analyze the strategies by which tutors adapt their teaching to individual students, so that we can synthesize these strategies in the SCHOLAR CAI system. To find out what strategies tutors use, we tape-recorded dialogues between various tutors and students on the topic of South American geography. Because SCHOLAR is a well-defined program, it is possible to analyze such ill-defined naturalistic data in precise terms, with respect to the structure and processing of information in SCHOLAR. We analyzed the dialogues concentrating on one aspect at a time. Based on our analyses, we propose in this paper several hypotheses about how the tutor relates his teaching to the individual student. We show how in modified form we have implemented some of these strategies in SCHOLAR. We further argue that the analytical method employed here could be extended to a wide range of conversational situations. This method (Dialogue Analysis) would permit psychologists to study questions about the interactive aspects of human processing that cannot even be considered with traditional laboratory methods.

Collins, A. M. Comparison of two teaching strategies in computer-assisted instruction. BBN Report No. 2885, 1974. Submitted to Instructional Science.

Three experiments were run using the SCHOLAR CAI system to teach geography to high-school students. The experiments compared a method of teaching derived from analysis of human tutors (Tutorial mode) vs. a method derived from programmed instruction (Block-Test mode). In the three experiments, Block-Test mode was systematically converged toward Tutorial mode in order to pinpoint what aspects of teaching strategy affected students' learning. Tutorial mode was significantly more effective in the first two experiments, and nonsignificantly in the third. The results indicated that the major factor affecting students' learning was the strategy that tutors use of reviewing the material in greater depth on a second pass. Allowing the students to ask questions, and the tutorial strategy for relating new material to the students' previous knowledge contributed only a small amount to the differences found in the first two experiments.

Grignetti, M. C., Hausmann, C., and Gould, L. An "intelligent" on-line assistant and tutor--NLS-SCHOLAR. In Proceedings of the National Computer Conference, San Diego, California, 1975, 775-781. (Partial support)

NLS-SCHOLAR is a prototype system that uses Artificial Intelligence techniques to teach computer-naive people how to use a powerful and complex editor. It represents

a new kind of Computer Assisted Instruction (CAI) system that integrates systematic teaching with actual practice, i.e., one which can keep the user under tutorial supervision while allowing him to try out what he learns on the system he is learning about.

NLS-SCHOLAR can also be used as an on-line help system outside the tutorial environment, in the course of a user's actual work. This capability of combining on-line assistance with training is an extension of the traditional notion of CAI.

The techniques used in NLS-SCHOLAR are general and can be applied to a wide variety of computer-related activities.

Collins, A. M., Warnock, E. H., Aiello, N., and Miller, M. W. Reasoning from incomplete knowledge. In D. G. Bobrow and A. M. Collins (Eds.), Representation and understanding. New York: Academic Press, 1975.

The paper describes how people use a variety of plausible, but uncertain, inferences to answer questions about which their knowledge is incomplete. This kind of reasoning is described in terms of how it is being implemented in the SCHOLAR CAI system. The paper also shows how people can be taught to reason in this way, using a Socratic tutorial method implemented in a system like SCHOLAR.

Collins, A. Education and understanding. In D. Klahr (Ed.) Cognition and instruction. Hillsdale, N. J.: Erlbaum Associates, 1975.

This chapter comments on chapters by Just and Carpenter and by Simon and Hayes on teaching understanding skills. The chapter argues that the most important aspect of understanding is how people use their knowledge about the world to fill in the information the text assumes. Thus there can be no easy way to educate people to understand, because they need to be taught both a huge amount of world knowledge and the understanding skills to use that knowledge effectively in reading.

Collins, A. and Grignetti, M. C. Intelligent CAI. BBN Report No. 3181, 1975. To be submitted to Science.

This paper describes the capabilities now available for building intelligent, tutorial CAI systems as exemplified by several systems including Tutor-SCHOLAR, Map-SCHOLAR, NLS-SCHOLAR and SOPHIE. The systems illustrate how a variety of sophisticated techniques can be used for tutoring different kinds of knowledge by carrying on dialogues in natural language. The systems have been developed to explore how to provide each student with his own personal, expert tutor.

Collins, A., Pew, R. W., and Adams, M. The effectiveness of an interactive map display in tutoring geography. In preparation.

This paper will describe the Map-SCHOLAR system and an experiment that compares how well students learn in Tutorial Mode, using (a) the interactive map display of Map-SCHOLAR (b) a static labeled map, and (c) an unlabeled map. The paper will also show how a new method called backtrace analysis can be used to pinpoint the effectiveness of different aspects of the tutoring strategy and the map system used in the experiment.

Intelligent CAI

Allan Collins

Mario C. Grignetti

Bolt Beranek & Newman Inc.

Cambridge, Mass. 02138

INTRODUCTION

If computerized instruction is ever to have a large impact on education, computer-assisted instruction (CAI) systems must have the flexibility and skill of a human teacher. In developing the SCHOLAR CAI system Carbonell (1) took a first step toward an intelligent tutorial CAI system. In SCHOLAR, knowledge was not stored as text, but in an interrelated network of facts and concepts, so that the knowledge could be used in a variety of ways. In short the attempt was to structure information like a human knowledge, so that the program could use its knowledge as flexibly as a human tutor does.

In this paper we will discuss the structure of the SCHOLAR system, some of the ways that the potential for intelligent CAI has been realized in current systems, and finally what is possible in the near future toward building intelligent tutorial systems.

The Context of SCHOLAR in CAI

Prior to Carbonell's SCHOLAR program, CAI had proceeded along several lines. Bryan (2) distinguished three broad categories. In the first, ad-hoc CAI, the student is given full control of the computer with a simple programming language and perhaps a series of tasks to perform. LOGO (3) provides one of the most interesting educational environments of this kind and indeed children learn some important cognitive skills in working with LOGO. The second category is games and simulation, where the student learns indirectly while participating in the game or simulation. The Plato

system's "How the west was won?" (4) is an excellent example of such a system where children learn the arithmetic operations in playing a variant of "Chutes and Ladders." Both these forms of CAI are highly interactive, but they are limited as teaching methods to certain kinds of knowledge.

The third category Bryan called controlled learning. Most programs in this category specify the possible sequences through a program, where different branches are taken depending on the student's responses to questions or problems. The sequence a student follows is usually deterministic, with a branch for each anticipated class of responses by the student (sometimes based on a keyword he might give). Some ingenious programs can be written in this way, such as the Socratic system (5) or the chemistry programs in the Plato System (6), but there are some inherent limitations to this approach. The student can not use natural language in his responses, and cannot ask any but specifically anticipated questions. The teacher has a considerable burden in the preparation of questions, answers, keywords, and branchings. From a system's point of view, the system has no real initiative or decision power of its own, nor any knowledge that is available other than at fixed points in the sequence.

The rigidity of this latter approach led to the development of "generative CAI" (7). The first CAI programs were based on mathematics and other well-defined subjects, where problems could be generated and answers evaluated by "algorithmic manipulation". This

was a major step toward representing a program's knowledge so that it could be used in a variety of ways. But the knowledge was limited to algorithmic domains.

Carbonell's contribution was to apply the idea of generative CAI to ill-defined verbal knowledge, in particular the domain of geography. To do this he used a semantic network (8) for representing knowledge about the world. In a semantic network, information is stored about concepts under different entries, much as in an encyclopedia, but according to a well-defined format. Every concept used to describe a given concept can itself be described elsewhere in the network. Thus the program can know about every concept it uses.

When information is represented in the general format a semantic network, then the structure of the network can be used by different procedures to formulate questions to the student, evaluate his answers, answer his questions, make inferences and computations, select new topics for discussion, etc. Freeing the information from the specific use it is to be put makes it available for use in a variety of ways. In this paper we will try to show some of the power for tutorial interaction that can be obtained by such an approach to CAI.

The Original SCHOLAR Program

Figure 1 presents a short protocol with SCHOLAR, showing some of the original system's capabilities. SCHOLAR selected topics on a

WHAT ARE THE PRINCIPAL CITIES OF BRAZIL?

RIO AND MAYBE BUENOS AIRES OR SAN PAULO

RIO DE JANEIRO AND SAO PAULO ARE CORRECT. YOU MISSPELLED SAO PAULO. BUENOS AIRES IS IN ARGENTINA, NOT IN BRAZIL. THE OTHER PRINCIPAL CITIES OF BRAZIL ARE BRASILIA, PORTO ALEGRE, SALVADOR, RECIFE, SANTOS, MANAOS, AND BELEM.

TRUE OR FALSE? THE LANGUAGE IN BRAZIL IS FRENCH.

Q/A

DO YOU WANT TO CHANGE THE GENERAL MODE OF THE INTERACTION TO QUESTION-ANSWERING MODE? PLEASE ANSWER Y OR N.

Y

OK, MR. JONES. LET'S GO AHEAD.

WHERE IS BRASILIA?

BRASILIA IS IN CENTRAL BRAZIL. IT IS IN THE BRAZILIAN HIGHLANDS.

TELL ME MORE ABOUT THE LOCATION OF BRASILIA?

THE LATITUDE OF BRASILIA IS -16. THE LONGITUDE IS -48.

WHAT IS LATITUDE?

A LATITUDE IS AN ANGULAR DISTANCE FROM THE EQUATOR. IT CAN BE CONSIDERED A PART OF A LOCATION.

WHAT IS THE MOST IMPORTANT DIFFERENCE BETWEEN BRASILIA AND RIO

THE PRIMARY DIFFERENCE IS: BRASILIA IS IN CENTRAL BRAZIL. BUT RIO DE JANEIRO IS IN SOUTHEASTERN BRAZIL.

IS THE CLIMATE OF SAO PAULO TROPICAL

NO. THE CLIMATE OF SAO PAULO IS TEMPERATE.

Fig. 1 Dialogue with the original SCHOLAR

random basis, weighted for importance. When it printed an asterisk, the student could respond to the question by SCHOLAR, direct a question to SCHOLAR, or issue a command such as halting or changing the mode of interaction. The student returned control to SCHOLAR by typing an asterisk and carriage return.

SCHOLAR's questions were constructed from the information in the semantic network, and were not prestored. The student's answers were evaluated by different procedures with respect to the information in the network, deciding whether the particular answer was correct, wrong, partly correct, or approximately correct. Student's questions were analyzed syntactically to determine what information was sought, and the semantic network searched to find the information. Different computations and inferences were applied, if the information was not stored directly. All these operations were carried out by procedures which operated independently of the specific information that was involved.

In Fig. 1 the questions by SCHOLAR illustrate different kinds of questions that could be generated. After the second question by SCHOLAR, the student changed the mode of interaction from mixed-initiative mode, where SCHOLAR asked him questions, to question-answering mode, where SCHOLAR waited for questions from the student. Other modes described below have since been added to SCHOLAR. Because the student can control the way he interacts with the system, he can choose the mode of interaction that he finds most effective. This is one of the important ways such a system

personalizes instruction.

The student then asked a series of questions to clarify and extend the information given to him about the cities of Brazil. When the student wants more information about something such as Brazilia, he can ask specifically what he wants to know. When he doesn't understand a word, such as latitude, he can have it explained. In this way the knowledge taught can be geared to the individual student's background, so as not to repeat what he already knows or go over his head. This is important to maintaining a student's motivation to learn.

The two questions about the location of Brasilia illustrate how a tutorial system can avoid overloading the student with too much information at one time. Each piece of information in the network is tagged to indicate its relative importance. The program gives only the most important information at any time, but the student can always ask for more information if he wants it.

The questions about the most important difference between Brasilia and Rio and about the climate of Sao Paulo illustrate the ability to use a semantic network to make appropriate computations and inferences. In the first case there is a procedure for comparing two things to find their similarities and/or differences. Each property of the two things is compared in the order of importance. Here the most important property on which the two things differ is found, and given as an answer to the student. The second case illustrates a combination of two inferences, a deduction

and a contradiction. Nothing about climate is stored with Sao Paulo, but Sao Paulo is in the Brazilian Highlands which has a temperate climate. By comparing tropical and temperate, SCHOLAR finds there is a contradiction and concludes the answer is "no". There are a large number of such inferential strategies that humans use, and only some of the more common ones have been implemented in SCHOLAR. But information in SCHOLAR is structured in such a way that it is possible to specify content-independent procedures to carry out different inferences.

This summarizes the major contributions of the original SCHOLAR system. There were also several severe limitations to the original SCHOLAR. First, the information in the program was restricted to static, verbal facts about geography, which are not very interesting in themselves. Second, the program was quite restricted in its ability to understand student answers and questions because of its limited language processing capability. Third, and perhaps most important there was no teaching strategy; the program merely generated questions randomly or answered student questions. We will try to show how later systems have overcome some of the limitations of the original SCHOLAR and at the same time exploited further its potential for tutorial interaction.

TEACHING STRATEGY

Analysis of Human Tutoring

In the original SCHOLAR there was no teaching strategy, but SCHOLAR's structure made it possible to model the way human tutors interact with students. By collecting tape recordings of different tutors teaching the same kind of information as SCHOLAR, it was possible to analyze how tutors adapt their teaching to the individual student (9). There were four crucial aspects of their tutoring strategy, that were subsequently modelled in SCHOLAR. They were: (a) the way tutors select topics, (b) the way they interweave questions and presentation, (c) their reviewing, and (d) their error correction strategy.

The topic selection strategy used by tutors produces a structure of topics and subtopics like an outline for a course. For example, the tutor might start off with a question like "Do you know any geographical features of South America?" If the student gives Cape Horn, for example, then the tutor would discuss Cape Horn for a while, including perhaps the Straits of Magellan as a subtopic. After covering the most important information about Cape Horn, the tutor would then ask about other geographical features, like the Amazon or the Andes. Each of these would be discussed briefly until the major geographical features are covered, at which point the tutor would pick a new topic such as regions or countries. Thus, the topics and subtopics form a nested outline structure, with the

tutor probing a little way into each subtopic, and then popping up to the previous topic when the important information is exhausted. The better the tutor, the more structure there is to the discussion.

The way the tutor interweaves questioning and presentation is the essence of how the tutor relates his teaching to the individual student. The dialogues showed that the tutors' questions occur at the top-level and beginning topics in the outline. This is because the tutor starts out asking questions to find out what the student already knows, and then presents new material that is related to the student's previous knowledge. The object seems to be to tie as much information as the student can assimilate into the structure of his previous knowledge (10).

Another important aspect of the tutorial strategy is reviewing. In the dialogues the better tutors went over the material on a second pass, asking about things the student didn't know the first time through, and adding more detail to the structure of information built up on the first pass. The tutorial method as a whole reflected a strategy Norman (10) refers to as "web teaching", where the teacher first tries to establish a framework of basic knowledge and then fills in more and more detail on subsequent passes, much like a spider spinning a web.

The fourth aspect of the dialogues important to individualizing instruction is the way tutors correct student errors. When students make a confusion between two concepts, the better tutors try to provide distinguishing properties between the concepts for the

student. For example, when one student confused Ecuador and Colombia, the tutor pointed out that Ecuador is a much smaller country and that Colombia is connected to Panama. By providing distinguishing characteristics, the tutor is giving the individual the most relevant information for remembering the distinction in the future.

Tutorial Mode in SCHOLAR

These four aspects of the human tutoring strategy were developed in a mode called Tutor-SCHOLAR (9). Like the human tutor, Tutor-SCHOLAR selects topics in order of importance, and goes into depth on those topics the student knows something about. It starts out asking questions always probing deeper until the student doesn't know an answer or the time is used up for that topic. When the student misses a question, it presents a little related information for the student to assimilate before going onto the next topic. It allocates its time between a first pass and a review pass. On the review pass it skips over what the student knew earlier. However, it asks about everything the student missed, or that was presented earlier. Anything the student remembers from the earlier pass leads the discussion into more depth on the review pass.

When the student suggests an answer that differs from what is stored, Tutor-SCHOLAR tries to find a basis for rejecting the student's answer. This involves an inferential comparison between what the student says and what is stored. If it can find a

contradiction, the program points out the basis for rejecting the student's answer plus anything it knows about the relation of the student's answer to the object in question. In this way it tries to give the student a basis for remembering the distinction in the future.

Figure 2 shows a transcript between Tutor-SCHOLAR and a naive student who was testing out the system. It shows the kinds of mistakes SCHOLAR makes in language understanding. But it also shows the interactive flavor of SCHOLAR with a tutoring strategy directing the conversation.

Systematic Evaluation of Teaching Methods

Because the information in SCHOLAR is distinct from the procedures used for teaching that information, it is possible to vary the teaching strategy while holding the information constant. This makes it possible to compare different teaching methods in a systematic manner. To evaluate the effectiveness of Tutor-SCHOLAR we compared it to a teaching strategy derived from programmed instruction, which was implemented in a mode called Block-SCHOLAR. Block-SCHOLAR selects topics in the same order as Tutor-SCHOLAR, but unlike Tutor-SCHOLAR it first presents material and then asks questions about the material presented.

Three experiments were run to compare Tutor-SCHOLAR and Block-SCHOLAR (11). The comparison was made by teaching students the same domain of information with the two versions of SCHOLAR, and

LET'S BEGIN BY TALKING ABOUT THE LOCATION OF BRAZIL. TRUE OR FALSE? BRAZIL IS IN NORTHEASTERN SOUTH AMERICA.

THAT IS FALSE

NO. BRAZIL IS IN NORTHEASTERN SOUTH AMERICA.

THE EASTERN COAST OF BRAZIL IS THE ATLANTIC. THE WESTERN BORDERING COUNTRIES ARE PERU AND COLOMBIA. THE SOUTHERN BORDERING COUNTRIES ARE URUGUAY AND ARGENTINA.

Because the student missed the question, SCHOLAR presents some related information about the location of Brazil, and then goes on to the next topic.

NEXT WE'RE GOING TO DISCUSS THE TOPOGRAPHY OF BRAZIL. THE PRINCIPAL RIVERS OF BRAZIL ARE----.

THE AMAZON AND THE ORINOCO.

THE AMAZON IS CORRECT. THE ORINOCO IS IN VENEZUELA AND COLOMBIA, NOT IN BRAZIL. THE OTHER PRINCIPAL RIVERS OF BRAZIL ARE THE TOCANTINS, THE SAO FRANCISCO, THE RIO NEGRO, AND THE MADEIRA.

THE SAO FRANCISCO IS IN EASTERN BRAZIL. IT IS IN THE BRAZILIAN HIGHLANDS. THE RIO NEGRO IS IN THE AMAZON JUNGLE. IT IS IN NORTHWESTERN BRAZIL.

Because the student knew about the Amazon, SCHOLAR takes it up as a topic for a while.

CORRECT OR INCORRECT? THE AMAZON IS NAVIGABLE.

POSSIBLY YES

NO. THE AMAZON IS NAVIGABLE.

SCHOLAR misunderstood the "possibly" and treated the answer as wrong.

THE AMAZON IS IN THE AMAZON JUNGLE. IT IS IN BRAZIL AND PERU. THE PRINCIPAL TRIBUTARIES ARE THE RIO NEGRO, THE MADEIRA, THE TOCANTINS, THE TAPAJOZ, THE PURUS, AND THE JURUA.

WHAT IS THE LENGTH OF THE AMAZON?

Fig. 2 Dialogue with Tutor-SCHOLAR

IS THE AMAZON A LAKE?

I DON'T KNOW IF THE AMAZON IS A LAKE, BUT IT IS A RIVER.

SCHOLAR found that both lakes and rivers were water, so it couldn't reject the idea.

NOW YOU CAN EITHER ANSWER MY QUESTION OR ASK A NEW ONE.

WHAT IS THE QUESTION?

WHAT IS THE LENGTH OF THE AMAZON?

5000 MILES

NO. THE LENGTH OF THE AMAZON IS 4,000 MILES.

Having exhausted its allotted time to rivers, SCHOLAR went onto the next subtopic under topography of Brazil.

THE PRINCIPAL MOUNTAINS OF BRAZIL ARE ----.

I AM NOT SURE, ARE THE ANDES IN BRAZIL?

IN WHAT YOU SAY, I DON'T RECOGNIZE THE WORDS "I", "AM" AND "SURE". TRY AGAIN.

ARE THE ANDES IN BRAZIL?

NO. THE ANDES ARE NOT IN BRAZIL, BUT IN VENEZUELA, COLOMBIA, ECUADOR, PERU, BOLIVIA, CHILE, AND ARGENTINA.

FEEL FREE TO ANSWER THE QUESTION YOU DIDN'T ANSWER BEFORE.

BRAZIL HAS NO MOUNTAINS.

NO. I DON'T KNOW WHAT YOU MEAN BY NO. THE CORRECT ANSWER IS THE BRAZILIAN HIGHLANDS.

SCHOLAR didn't understand the answer, but proceeded quite reasonably.

THE BRAZILIAN HIGHLANDS ARE IN SOUTHEASTERN BRAZIL. THEY ARE NEAR THE ATLANTIC.

WHAT IS THE PRINCIPAL PLATEAU OF BRAZIL?

The dialogue continued discussing different aspects of Brazil, but we will break here to the beginning of the second pass.

Fig. 2 Dialogue with Tutor-SCHOLAR (cont)

NOW WE WILL GO OVER THE MATERIAL AGAIN. LET'S BEGIN BY TALKING ABOUT THE LOCATION OF BRAZIL.

PLEASE INDICATE IF THE FOLLOWING STATEMENT IS CORRECT OR INCORRECT: BRAZIL IS IN NORTHEASTERN SOUTH AMERICA.

TRUE

THAT'S RIGHT. BRAZIL IS IN NORTHEASTERN SOUTH AMERICA.

Because on this pass the student was correct, SCHOLAR asked questions about the information that was presented on the first pass.

THE EASTERN COAST OF BRAZIL IS ----.

ATLANTIC SEA.

VERY GOOD. THE ATLANTIC IS CORRECT.

THE WESTERN BORDERING COUNTRIES OF BRAZIL ARE ----.

The dialogue continued through the second pass.

Fig. 2 Dialogue with Tutor-SCHOLAR (cont)

measuring their learning by comparing pre-test and post-test scores on the material covered. In the three experiments, Block-SCHOLAR was systematically converged toward Tutor-SCHOLAR in order to pinpoint what aspects of teaching strategy affected student's learning. Tutor-SCHOLAR was significantly more effective in the first two experiments, and nonsignificantly in the third. The results indicated that the major factor affecting student's learning was the strategy that tutors use of reviewing the material in greater depth on a second pass. Allowing the students to ask questions, and the tutorial strategy of relating new material to the student's previous knowledge contributed a smaller amount to the greater effectiveness of Tutor-SCHOLAR.

The fact that SCHOLAR can be used to test particular aspects of teaching methods makes it potentially a valuable tool for educational research. The possibility of trying out single modifications in teaching strategy to see their effects on student's learning rate is unique. Human teachers of course can make such modifications in their own teaching strategies, but there is no way to control all the other factors that might vary as they change strategy. However, any specific version of SCHOLAR is a fixed system, and so an unbiased comparison can be made using any number of subjects. In this way th accumulation of systematic knowledge about teaching methods can occur.

TUTORING DIFFERENT TYPES OF KNOWLEDGE

One of the limitations of the original SCHOLAR was that it was restricted to teaching verbal facts about geography. The SCHOLAR system itself has been extended to encompass two other kinds of knowledge: visual knowledge about maps in the geography domain, and procedural knowledge about how to use a computer text-editing system called NLS (12). A related program called SOPHIE (13) tutors the diagnostic skills needed in electronic troubleshooting. In this section we will try to show the generality of this approach to CAI, and also some of the specific adaptions that have occurred in applying it to different domains of knowledge.

Tutoring Visual Knowledge

In order to explore the tutoring of visual information in an integrated manner with verbal information, we developed a Map-SCHOLAR System (14). The system can discuss with the student different maps that change dynamically according to the context of the discussion. To do this a graphic structure was created which parallels the structure in the semantic network. The elements in the map display therefore can be referred to either by their name, or by pointing to them, or both. Map-SCHOLAR both asks and answers map-related questions and provides relevant map information when the student makes a mistake. It has all the capabilities of Tutor-SCHOLAR with the addition of the map capabilities.

Figure 3 illustrates some of the variety of interactions possible with Map-SCHOLAR. The first panel illustrates how Map-SCHOLAR asks map-related questions, evaluates the student's answers, and corrects his mistakes. First, the dots indicating the location of the cities appear unlabelled on the map of Brazil and start blinking. Then SCHOLAR asks the student to name the blinking cities. When he responds, it tells him which answers were correct and prints their names on the map. Because he erroneously gave Lima as an answer, Map-SCHOLAR pointed out that Lima is in Peru and showed where Lima is on the map. Thus Map-Scholar gives both verbal and visual feedback to help the student learn the material.

The second panel shows how context affects the map display. The topic is the Amazon, which appears in this context on the map of Brazil, the overall topic. The question asks the student to point at the cities along the Amazon in the order named. The dots for the three cities first appear unlabelled, and only after the student has answered do the labels appear. Unlike the first map, this map shows only the cities on the Amazon and their relation to the Amazon. There is also expansion of detail so that a city like Belem, which was not important enough to be included among the cities of Brazil, is included with the subtopic of the Amazon. Because the map changes dynamically as the context changes and as the student interacts with the system, the students attention is focused on the relevant information exclusively and questions can be posed in a visual form not possible with a static map display.

NOW LET'S SEE WHAT YOU REMEMBER ABOUT THE CITIES OF BRAZIL.
PLEASE NAME THE PRINCIPAL CITIES OF BRAZIL NOW BLINKING
ON THE DISPLAY SCREEN.

MANAOS SAO PAULO AND LIMA

MANAOS AND SAO PAULO ARE CORRECT. LIMA IS IN PERU, NOT IN BRAZIL.
THE PRINCIPAL CITIES OF BRAZIL ARE BLINKING ON THE SCREEN.

RIO DE JANEIRO IS IN SOUTHEASTERN BRAZIL.
IT IS ON GUANABARA BAY AND THE ATLANTIC.

BRASILIA IS IN CENTRAL BRAZIL.
IT IS FAR FROM THE OCEAN.

Fig. 3 Interactions with Map-SCHOLAR

PLEASE POINT TO THE FOLLOWING CITIES OF THE AMAZON
IN THE ORDER IN WHICH THEY APPEAR BELOW:
MANAOS, BELEM, AND IQUITOS
DON'T FORGET TO LET ME KNOW WHEN YOU ARE FINISHED,
PLEASE REMEMBER TO TYPE AN ASTERISK * FOLLOWED BY A
CARRIAGE RETURN.

**

MANAOS IS CORRECT. YOU DID NOT POINT AT BELEM AND IQUITOS CORRECTLY.
THE CITIES OF THE AMAZON ARE BLINKING ON THE SCREEN.

Fig. 3 Interactions with Map-SCHOLAR (cont)

LET'S BEGIN BY TALKING ABOUT THE TOPOGRAPHY OF VENEZUELA.
THE PRINCIPAL LAKE OF VENEZUELA IS BLINKING, PLEASE NAME IT.

I DON'T KNOW

THE PRINCIPAL LAKE OF VENEZUELA IS BLINKING ON THE SCREEN.

LAKE MARACAIBO IS IN NORTHWESTERN VENEZUELA.
THE PRINCIPAL MINERAL IS OIL.

IS THIS COUNTRY COLOMBIA?

YES, THAT'S COLOMBIA

WHERE IS THE CAPITAL OF VENEZUELA?

CARACAS IS BLINKING.

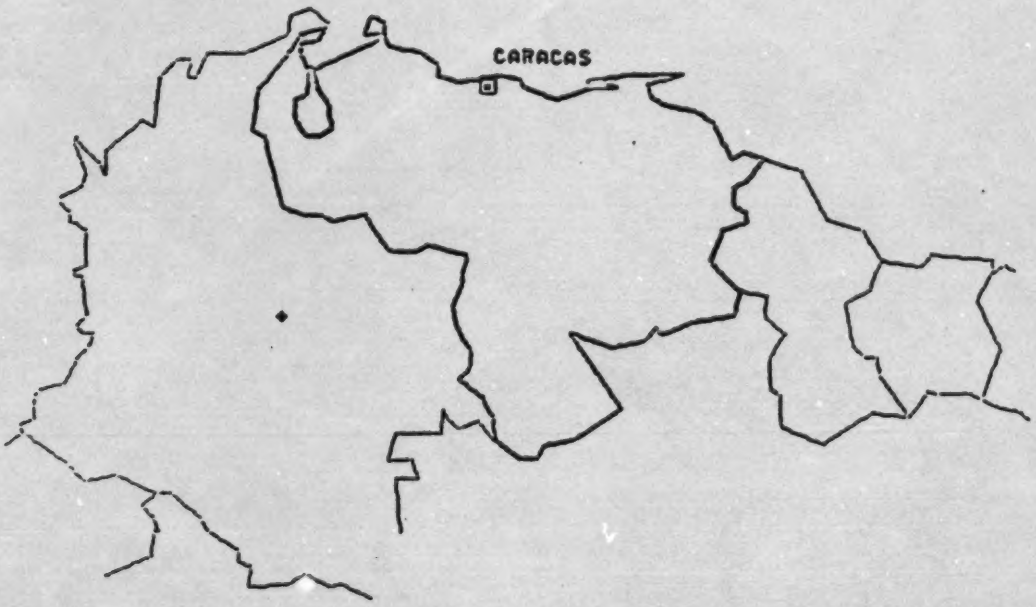

Fig. 3 Interactions with Man-SCHOLAR (cont)

The third panel shows the system's potential for tutorial interaction. When the student didn't know about Lake Maracaibo, Map-SCHOLAR showed it on the screen and added the related verbal information about the oil there. The two questions by the student illustrate some of the variety of questions the student can ask Map-SCHOLAR to clarify or amplify the information given (14). The first question involves both pointing at and naming Colombia to ask if that is the country near Lake Maracaibo. The second question shows another kind of map question. The subject verbally asks where the capital of Venezuela is, perhaps to find out how far away it is. SCHOLAR figures out semantically that the capital is Caracas, and then visually shows where Caracas is by blinking it (it is the double square). These examples illustrate some of the power for tutorial interaction that can be obtained by a close integration between semantic and visual knowledge.

There is now substantial evidence in the psychological literature (15) that people remember imageable material better than non-imageable material. Furthermore, if they use image strategies for remembering (16), they remember any given information better than if they use other strategies. Hence the fact that information is presented visually should make it more memorable.

As Collins & Quillian and Norman (10) argue, the best way to learn something is to relate it as much as possible to whatever information one already knows. Hence, even non-visual information like the fact that the Manaos has a tropical climate, will be

learned better, if one can see where Manaos is. This is true for two reasons. First, because when Manaos is located visually, it will be remembered better, and so facts that are related to it will also be remembered better. Second, if a student sees that Manaos is on the Amazon, then its climate can be related to any knowledge about the climate of the Amazon. Thus, information that seems not to depend on imagery should be remembered better in a visual context. For these reasons we expect the map facility, to have a substantial impact on how much students learn.

We have conducted an experimental evaluation of the map system using the comparative method described earlier (11). The test compared student's learning with Tutor-SCHOLAR using the map system vs. a labeled map vs. an unlabelled map. The experiment found an advantage of the map system over either of the static maps. We are using a technique called "backtrace analysis", which involves comparing the specific information each student learned with how that information was discussed, in order to pinpoint what aspects of the map system led to better learning by the students.

Tutoring Procedural Knowledge

NLS-SCHOLAR (17) is a prototype system to teach computer-naive people how to use the powerful NLS text-editing system (12). This teaching is accomplished by presenting a sequence of lessons. During each lesson the student may interact with the system by asking and answering questions, performing tasks which are posed by

the system, and performing tasks of his own choosing. Tasks are executed on an actual NLS system. Those tasks which have been posed are evaluated by the system, and the student is given encouragement, advice, and assistance.

NLS-SCHOLAR has been designed with the belief that procedural knowledge is best learned 'by doing'. It is an example (18) of a new kind of CAI system that integrates systematic teaching with actual practice, i.e., one which can keep a student under "intelligent" tutorial supervision while allowing him to try out what he learns on the very system he is learning about. Thus the system "knows" what the student is doing and can point out his mistakes, give specific help, show him how to do things and even do them for him.

NLS-SCHOLAR delivers a series of lessons designed for gradual understanding of NLS concepts and commands. Within these lessons, the system pauses to ask the student questions and to propose editing tasks for him to perform using NLS. A student's responses to questions and his performance of tasks are evaluated by the system and if he makes an error, the nature of his mistake is pointed out and appropriate action is taken. For example, if a question is answered unsatisfactorily, NLS-SCHOLAR proposes another question of the same kind. If a task is performed incorrectly, depending on the magnitude of the error, NLS-SCHOLAR either resets it for the student to try again, or asks him to proceed and try to fix his mistake, aided by the information NLS-SCHOLAR provides.

The user can formulate requests in relatively unconstrained English. The requests can be questions about NLS concepts or about the state of his work, requests for help in doing a task, or even NLS commands expressed in English. The system is "aware" of what the user is currently doing so that his requests for help can be answered within the context of the problem he is working on. Thus NLS-SCHOLAR not only tells him "The general procedure is..." but also "In your case, what you should do is...".

NLS-SCHOLAR has the ability to use the NLS file a student is currently working on to show him how to perform editing actions. This gives the system much of the flavor of a human tutor, as if he were taking the student's place at the terminal and saying "Watch me do it for you".

The flavor of NLS-SCHOLAR is best conveyed by an annotated protocol, shown in Fig. 4, which was obtained on-line using a version of the system. In the course of a lesson, students learn how to change the contents of a menu by performing editing operations. The protocol starts at a point well along in the student's learning of NLS -- he has been told about NLS files, how to load them, print them, delete and insert statements, etc. He is about to be taught how to use the Substitute command to effect a change in the menu. Notice that what the student actually typed is underlined and that our annotations appear in italics.

The capabilities of NLS-SCHOLAR allow students to learn from explanation, learn by doing, and learn by asking questions. Their

```
BREAKFAST MENU

1  JUICE
   1A  ORANGE
   1B  GRAPEFRUIT
2  CEREAL
   2A  OATMEAL
       2A1  WITH RAISINS
   2B  CREAM OF WHEAT
   2C  CORN FLAKES
3  EGGS
   3A  SCRAMBLED
   3B  FRIED
       3B1  SUNNY-SIDE-UP
       3B2  OVER-EASY
   3C  BOILED
4  BEVERAGE
   4A  HOT CHOCOLATE
   4B  TEA
       4B1  WITH LEMON
       4B2  WITH SUGAR AND CREAM
   4C  COFFEE
```

SUBSTITUTE WORD IN STATEMENT

Before we end this lesson, I'd like to show you how to change the content of statements which have already been inserted in your file.

You've learned how to correct errors by deleting an entire statement and inserting a new one in its place. The Substitute command may be used to change just a word or even a single character at a time. For example, here's how you can change a word in statement 2A1 so that it reads WITH DATES instead of WITH RAISINS.

```
EDIT C: (Su )bstitute C: (W )ord in  C: (S )tatement at  A: (2A1
)(<CR>);
 <New WORD> T: (DATES)(<CR>);
 <Old WORD> T: (RAISINS)(<CR>);
Finished? Y/N: (Y) OK: (<CR>);
Substitutions made: 1
EDIT C: (Do )ne OK: (<CR>);
```

NLS-SCHOLAR performs a command for the student much as a human tutor would by leaning over the student and typing the command on the student's terminal. Parentheses enclose what the "tutor" actually "types", separating it from the echoes and responses printed by NLS.
<CR> is just a symbol to denote that the "tutor" depressed the return key. The semicolon is NLS's echo to <CR>.

Fig. 4 Dialogue with NLS-SCHOLAR

You can see that I've specified that I want to substitute one word in statement 2A1 for another; the new word DATES is to be substituted for the old word RAISINS.
(There is no restriction that the items substituted for one another be of the same length.)

To do this I typed only 'Su W S 2A1 <CR>' to produce the first line; I typed 'DATES <CR>' and 'RAISINS <CR>' to produce the second and third. The remaining characters are all printed by NLS.

NLS asks 'Finished?' since more than one substitution can be made at a time. If I had typed 'N' for no instead of 'Y' for yes, it would have prompted for another <New WORD> and <Old WORD> pair.

After I typed 'Y' NLS asks for further confirmation with OK:
to which I responded with a <CR>.

When the command has been executed, NLS tells how many substitutions have been made. If there had been two instances of RAISINS in statement 2A1, both would have been changed to read DATES.

Statement 2A1 is now the current statement. Please print it.

Student typing is underlined.

TASK 41

EDIT C: /
==>WITH DAT
EDIT C: ↑
2A OATMEAL

The student confuses the \ command, which prints the current statement, with the / command that shows the current position of the control marker. Realizing his mistake, he fumbles with the other one-character commands he can remember. First he tries ↑ which prints the previous statement (2A), and makes it become the current statement.

EDIT C: %
2A1 WITH DATES

Next the student depresses the LINE FEED key which echoes as %, giving him the next statement (2A1), making it current.

EDIT C: Done OK: ;

You printed too many statements.
This is what I wanted you to print:
2A1 WITH DATES

The task is evaluated.

Please redo just the printing
part of this task. Your file is unchanged.

NLS-SCHOLAR is really determined to get the student to review how to print the current statement.

Fig. 4 Dialogue with NLS-SCHOLAR (cont)

continuation of TASK 41

EDIT C: "What command prints the current statement?"

THE USER PRINTS THE CURRENT STATEMENT USING THE
\ COMMAND.

Failing to remember the appropriate one-character command, the student gives up and asks for help. Questions can be asked anytime it is the student's turn to type. NLS-SCHOLAR answers this question by retrieving information from its own internal, descriptive data base.

continuation of TASK 41

EDIT C: \
 2A1 WITH DATES
EDIT C: Done OK:_;

QUESTIONS?

"_

The student chooses to ask no questions at this time.

Try the Substitute command yourself by substituting the word
OAT for CORN in the statement containing "CORN FLAKES".

TASK 42

EDIT C: "What statement contains "CORN"?"

THE STATEMENT CONTAINING "CORN" IS:
 2C CORN FLAKES

The student wants to know what the correct statement number is for him to type. The system obtains the answer by actually looking into the student's work space -- the answer is not stored (it cannot be!) in the internal data base. The system interprets correctly most of the common paraphrases of this type of question, e.g.
"What is the statement containing ..."
"What statement contains ..."
"Where is ...", etc.

Fig. 4 Dialogue with NLS-SCHOLAR (cont)

```
continuation of TASK 42

EDIT C: Substitute C: Word in  C: Statement at  A: 2C;
 <New WORD> T: CORN;
 <Old WORD> T: OAT;
Finished? Y/N: Y  OK:_;
Substitutions made: 0
EDIT C: Done OK:_;
```

The student switches around the new and the old words, so no change is made.

```
You should have altered the file
so that this part of it
    2B CREAM OF WHEAT
    2C CORN FLAKES
 3 . . .

would look like this:
    2B CREAM OF WHEAT
    2C OAT FLAKES
 3 . . .

But you did not alter the file.

        Please try to repair your
mistake.  The file is as you left it.

continuation of TASK 42

EDIT C: "How does one do this?"
```

NLS-SCHOLAR shows the student what the result of this command should have been if he had performed the task correctly as opposed to the result which he obtained. With this information, the student can "debug" his performance of the task.

The student is lost and asks for help.

```
THE USER TYPES 'SUBSTITUTE', FOLLOWED BY 'WORD',
'STATEMENT', '2C', <CR>, 'OAT', <CR>,
'CORN', <CR>, 'Y', <CR>, 'DONE', AND <CR>.
```

NLS-SCHOLAR can show him what to do, as well as...

```
continuation of TASK 42

EDIT C: "Please do it for me"
```

...actually do it for him!

```
EDIT C: (Substitute ) C: (Word ) in C: (Statement ) at A: (2C)(<CR>);
 <New WORD> T: (OAT)(<CR>);
 <Old WORD> T: (CORN)(<CR>);
Finished? Y/N: (Y) OK: (<CR>);
Substitutions made: 1
EDIT C: (Done ) OK: (<CR>);
```

Fig. 4 Dialogue with NLS-SCHOLAR (cont)

tight integration within a working environment makes NLS-SCHOLAR a powerful tutorial CAI system.

Tutoring Diagnostic Skills

SOPHIE (13) reflects an attempt to extend Carbonell's notion of mixed-initiative CAI for the purpose of encouraging a wider range of student initiatives. Unlike previous tutorial systems which attempt to mimic the roles of a human teacher, SOPHIE tries to create a "reactive" environment in which the student learns by trying out his ideas rather than by instruction. To this end, SOPHIE incorporates a "strong" model of its knowledge domain along with numerous heuristic strategies for answering a student's questions, providing him with critiques of his current solution paths, and generating alternative theories to his current hypotheses. In essence, SOPHIE enables a student to have a one-to-one relationship with an "expert" who helps the student create, experiment with, and debug his own ideas.

SOPHIE's expertise is derived from an efficient and powerful inferencing scheme that uses multiple representations of knowledge including (a) simulation models of the domain (b) procedural specialists which contain logical skills and heuristic strategies for using these models, and (c) semantic nets for encoding time-invariant factual knowledge. The power and generality of SOPHIE stems, in part, from the synergism obtained by focusing the diverse capabilities of the procedural specialists on the

"intelligent" manipulation, execution, and interpretation of its simulation models.

In the basic scenario, SOPHIE acts as an electronics lab instructor who helps the student transform his classroom knowledge of electronics into an experiential, intuitive knowledge of its meaning and application. It does this by interacting with the student while he is debugging a malfunctioning piece of equipment (19). The student can perform any sequence of measurements, ask either specific questions about the implications of these measurements for more general hypothetical questions, and even ask for advice about what to consider next, given what he has discovered thus far. At any time SOPHIE may encourage the student to make a guess as to what he thinks might be wrong given the measurements he has made thus far. If he does, SOPHIE will evaluate his hypothesis by taking into consideration all the information he should have been able to derive from his current set of measurements. If any of this information is logically contradicted by the hypothesis, SOPHIE identifies and explains these contradictions. Likewise SOPHIE can judge the merits of any particular measurement with respect to the prior sequence of measurements he has made. For example, his new measurement may be logically redundant in the sense that no new information can possibly be derived from it (an extremely complex task to determine). SOPHIE can also decide if this measurement performs a reasonable split of the hypothesis space of possible faults which have not yet been ruled out by prior measurements.

It should be noted that the scenario contains quite a variety of logical tasks (i.e., hypothesis evaluation, hypothesis formation, redundancy checking, hypothetical question answering) each one of which requires a substantial amount of deep logical inferencing. One of the basic challenges in constructing SOPHIE was creating an inference system which could perform this wide range of tasks efficiently (so that it could be used in real time) and at the same time have it be robust in the sense of handling all realistic queries.

Because SOPHIE was designed as an environment in which students could create and articulate ideas, it was necessary to have a powerful natural language processor to communicate with students. A student will become frustrated if he has to try several ways of expressing an idea to get a response. In addition he will become bored if there is a long delay (say 10 secs) before the system replies. And because students begin to assume the system shares their "world-view", SOPHIE must cope with contextually-dependent references, deletions, and ellipses. SOPHIE's natural language processor is based upon a "semantic grammar" technique, in which concepts like "measurement" or "circuit element" trigger expectations about what things should appear in the student's input. SOPHIE has demonstrated that natural language processing has advanced far enough to deal with these three kinds of difficulties well enough to build friendly, but sophisticated tutorial systems.

THE FUTURE OF INTELLIGENT CAI

The thrust of this paper has been to show what kind of capabilities are now available for building genuinely intelligent CAI systems. The domain of such systems is virtually unlimited; it is not restricted, for example, to drill and practice or mathematics. The language capabilities of current systems are not equal to those of a human, nor will they be in the foreseeable future, but they are good enough to sustain practical systems.

The Plato system (6) has shown that it is possible to build both interesting and cost-effective CAI systems in a time-shared computer environment. They have accomplished this by using a variety of teaching techniques: the Socratic method, generative CAI, games and simulations, programmed instruction, etc. Intelligent CAI is an attempt to go beyond the technology in the Plato system to explore how to build greater intelligence into tutorial systems, while at the same time utilizing many of the educational techniques employed so successfully in Plato.

Intelligent CAI systems are now both costly to build (above $100,000) and to use (about $10-$20 per hour). But, the cost of computing continues to decrease while teacher's salaries are rising. Hence the cost of running such systems should be competitive in comparison to the cost of human tutoring within a short time, especially where there are few skilled teachers available, as with teaching computer text-editing. The effective cost of building such systems depends on how much they are used. If they are used

heavily, then the large cost of building them will be worth the investment; otherwise not. It is at least possible that one of the current systems will be used enough to justify the development expense, though they were built only as prototype systems. The test though will be the development of such a system for a school setting where large numbers of people are being taught.

The payoff in intelligent CAI comes from personalizing the learning process. Personalization is effective in many ways: by forcing the student to participate in learning; by teaching at the level of his individual knowledge; by providing a setting where the student can try out his own ideas and make mistakes; by freeing the student from peer pressure; by addressing the student's individual confusions, etc. These advantages make it worthwhile to give intelligent CAI a serious trial.

References and Notes

1. J.R. Carbonell, IEEE Trans. Man-Mach. Sys. MMS-11, 190 (1970).

2. G.L. Bryan, Comp. & Automat. 18, No. 3, 1 (1969).

3. S. Papert, Prog. Learn. & Ed. Tech. 9, No. 5, (1972). I.P. Goldstein, AITR-294, (AI Lab., MIT, Cambridge, Mass., 1974). W. Feurzeig & G. Lukas, Ed. Tech. 12, No. 3, 39 (1972).

4. C. Resnick, Computational of Models of Learners for Computer Assisted Learning, Unpublished Doctoral Dissertation. (U. of Illinois, Urbana, Ill., 1974).

5. J. Swets & W. Feurzeig, Science 150, 572 (1965).

6. D.L. Bitzer & R.L. Johnson, Proc. of IEEE 59, 960 (1971) D.L. Bitzer, B.A. Sherwood, P. Tenczar, CERL Rpt. X-37, (Computer-based Education Research Laboratory, U. of Illinois, Urbana, Ill., 1972).

7. L. Uhr, Proc. 24th ACM National Conf. (New York, 1969) p. 125. W.R. Uttal, T. Pasick, M. Rogers, and R. Hieronymus. Comm. 243. (Mental Health Research Inst., Ann Arbor, Mich.,

1969). J.D. Wexler, IEEE Trans. Man-Mach. Syst., MMS-11, 181, 1970.

8. M.R. Quillian in Semantic Information Processing, M. Minsky Ed. (MIT Press, Cambridge, Mass., 1968) p. 216. R. Simmons in Computer Models of Thought and Language, R.C. Schank & K. Colby, Eds. (Freeman, San Francisco, 1973) p. 63.

9. A. Collins, E.H. Warnock, and J.J. Passafiume in The Psychology of Learning and Motivation, Vol. 9, G.H. Bower, Ed. (Academic Press, New York, 1975).

10. A. Collins and M.R. Quillian in Cognition in Learning and Memory, L.W. Gregg, Ed., (Wiley, New York, 1972) p. 117. D.A. Norman in Contemporary Issues in Cognitive Psychology: The Loyola Symposium, R.L. Solso, Ed. (Halsted Press, New York, 1973).

11. A. Collins, BBN Report No. 2885. (Bolt Beranek & Newman, Cambridge, Mass., 1974).

12. NLS, the On Line System, is a sophisticated modular system which is being used increasingly as an aid in writing, re-organizing, indexing, publishing, and disseminating information of all kinds. It was developed by Douglas Engelbart and his co-workers at the Augmentation Research Center of the Stanford Research

Institute.

13. J.S. Brown and R.R. Burton in Representation and Understanding, D.G. Bobrow and A. Collins, Eds. (Academic Press, New York, 1975) p. 311. J.S. Brown, R.R. Burton, and A.G. Bell, Intl. J. Man-Mach. Stud., in press (1975).

14. A. Collins and E.H. Warnock, BBN Report No. 2833 (Bolt Beranek & Newman, Cambridge, Mass., 1974).

15. A. Paivio, Imagery and Verbal Processes. (Holt, Rinehart, and Winston, New York, 1971).

16. D.A. Norman, Memory and Attention. (Wiley, New York, 1969). G.H. Bower in Cognition in Learning and Memory, L.W. Gregg, Ed. (Wiley, New York, 1972) p. 51.

17. M.C. Grignetti, C. Hausmann, and L. Gould in Proc. of National Computer Conf. (Anaheim, Calif., 1975) p. 775. M.C. Grignetti, L. Gould, A.G. Bell, C.L. Hausmann, G. Harris, and J.J. Passafiume BBN Report No. 2969. (Bolt Beranek & Newman Inc., Cambridge, Mass., 1974).

18. Other examples are reported in A. Barr, M. Beard, and R.C. Atkinson, TR-228 (Psychology and Education Series, Stanford U. Stanford, Calif., 1974) and in D.R. Gentner, M.R. Wallen and

P.L. Miller, A Computer-based System for Studies in Learning, (Center for Human Information Processing, UCSD, LaJolla, Calif., 1974).

19. Although the domain of knowledge under consideration is electronics, the reasoning and linguistic paradigms underlying SOPHIE are applicable to many domains outside of electronics.

20. This research was sponsored by the Personnel and Training Research Programs, Psychological Sciences Division, Office of Naval Research, under Contract No. N00014-71-C-0228, Contract Authority Identification Number, NR 154-330. We would like to thank all those who helped in the development of the systems described in particular Nelleke Aiello, Alan Bell, Richard Burton, Jaime G. Carbonell, Laura Gould, Susan Graesser, Gregory Harris, Catherine Hausmann, Mark Miller, Joseph Passafiume, Eleanor Warnock, and especially John Seely Brown and the late Jaime R. Carbonell.

DISTRIBUTION LIST

4 Dr. Marshall J. Farr, Director
Personnel & Training
Research Programs
Office of Naval Research
Arlington, VA 22217

1 Director
ONR Branch Office
495 Summer Street
Boston, MA 02210
ATTN: C. M. Harsh

1 Director
ONR Branch Office
1030 East Green Street
Pasadena, CA 91101
ATTN: E. E. Gloye

1 Director
ONR Branch Office
536 South Clark Street
Chicago, IL 60605
ATTN: M. A. Bertin

1 Office of Naval Research
Area Office
207 West 24th Street
New York, NY 10011

2 Director
Advanced Research Projects
Agency
1400 Wilson Boulevard
Arlington, VA 22209
Attention: Program Management
DODAAD Code
HXI241

1 STOIAC
Battelle Memorial Institute
505 King Avenue
Columbus, Ohio 43201
Attention: H8-1 Code
79986

6 Director
Naval Research Laboratory
Code 2627
Washington, DC 20390

12 Defense Documentation
Center
Cameron Station,
Building 5
5010 Duke Street
Alexandria, VA 22314

1 Chairman
Behavioral Science Department
Naval Command and Management
Division
U.S. Naval Academy
Luce Hall
Annapolis, MD 21402

1 Chief of Naval Technical
Training
Naval Air Station Memphis(75)
Millington, TN 38054
ATTN: Dr. G. D. Mayo

1 Chief of Naval Training
Naval Air Station
Pensacola, FL 32508
ATTN: CAPT Bruce Stone, USN

1 TACTEC
Battelle Memorial Institute
505 King Avenue
Columbus, Ohio 43201
Attention H8-1 Code
79986

1 Defense Contract Administration
Services Region
666 Summer Street
Boston, MA 02210
Attention: DODAAD Code
52202A

6 Director
Naval Research Laboratory
Washington, D.C. 20375
Attention: DODAAD Code
N00173
Code 2629

1 Program Coordinator
Bureau of Medicine and Surgery
Code 71G
Department of the Navy
Washington, D.C. 20372

1 Commanding Officer
Naval Medical Neuropsychiatric
Research Unit
San Diego, CA 92152

1 Dr. Harold Booher
NAVAIR 415C
Naval Air Systems Command
5600 Columbia Pike
Falls Church, VA 22042

1 CAPT John F. Riley, USN
Command Officer
U.S. Naval Amphibious School
Coronado, CA 92155

1 Special Assistant for Manpower
OASN (M&RA)
The Pentagon, Room 4E794
Washington, D.C. 20350

1 CDR Richard L. Martin, USN
COMFAIRMIRAMAR F-14
NAS Miramar, CA 92145

1 Research Director, Code 06
Research and Evaluation
Department
U.S. Naval Examining Center
Great Lakes, IL 60088
ATTN: C. S. Winiewicz

1 Commander
Naval Air Reserve
Naval Air Station
Glenview, IL 60026

1 Commander
Naval Air Systems Command
Department of the Navy
AIR-413C
Washington, D.C. 20360

1 Mr. Lee Miller (AIR 413E)
Naval Air Systems Command
5600 Columbia Pike
Falls Church, VA 22042

1 Dr. John J. Collins
Chief of Naval Operations
(OP-987F)
Department of the Navy
Washington, D.C. 20350

1 Technical Library (Pers-11B)
Bureau of Naval Personnel
Department of the Navy
Washington, D.C. 20360

1 Dr. Richard J. Niehaus
Office of Civilian
Manpower Management
Code 06A
Department of the Navy
Washington, D.C. 20390

1 Dr. James J. Regan
Technical Director
Navy Personnel Research
and Development Center
San Diego, CA 92152

1 Chief
Bureau of Medicine and Surgery
Code 413
Washington, D.C. 20372

1 Mr. Arnold Rubinstein
Naval Material Command
(NMAT-03424)
Room 820, Crystal Plaza #6
Washington, D.C. 20360

1 Superintendent
Naval Postgraduate School
Monterey, CA 92940
ATTN: Library (Code 2124)

1 Technical Library
Naval Ship Systems Command
National Center, Building 3
Room 3S08
Washington, D.C. 20360

1 Chief of Naval Training Support
Code N-21, Building 45
Naval Air Station
Pensacola, FL 32508

1 Dr. H. Wallace Sinaiko
c/o Office of Naval Research
(Code 450)
Psychological Sciences Division
Arlington, VA 22217

1 Commandant
U. S. Army Institute of
Administration
ATTN: EA
Fort Benjamin Harrison, IN 46216

1 Armed Forces Staff College
Norfolk, VA 23511
ATTN: Library

1 Commander
U. S. Theatre Army Support
Command, Europe
ATTN: Asst. DCSPER (Education)
APO New York 09058

1 Commanding Officer
Naval Personnel Research
and Development Center
San Diego, CA 92152

1 Mr. George N. Graine
Naval Ship Systems Command
(SHIPS 03H)
Department of the Navy
Washington, D.C. 20360

1 Commanding Officer
Service School Command
U.S. Naval Training Center
San Diego, CA 92133
ATTN: Code 303

1 Dr. William L. Maloy
Principal Civilian Advisor
for Education and Training
Naval Training Command,
Code 01A
Pensacola, FL 32508

1 Dr. Martin F. Wiskoff
Navy Personnel Research
and Development Center
San Diego, CA 92152

1 Chief, Unit Training and
Educational Technology
Systems
U. S. Army Research
Institute for the Behavioral
and Social Sciences
1300 Wilson Boulevard
Arlington, VA 22209

1 Director of Research
U. S. Army Armor Human
Research Unit
ATTN: Library
Building 2422 Morade Street
Fort Knox, KY 40121

1 U. S. Army Research Institute
for the Behavioral and
Social Sciences
1300 Wilson Boulevard
Arlington, VA 22209

1 Commanding Officer
ATTN: LTC Montgomery
USADC - PASA
Ft. Benjamin Harrison, IN 46249

1 Dr. John L. Kobrick
Military Stress Laboratory
U. S. Army Research Institute
of Environmental Medicine
Natick, MA 01760

1 Commandant
United States Army
Infantry School
ATTN: ATSIN-H
Fort Benning, GA 31905

1 U. S. Army Research Institute
Commonwealth Building
Room 239
1300 Wilson Boulevard
Arlington, VA 22209
ATTN: Dr. R. Dusek

1 Mr. Edmund F. Fuchs
U. S. Army Research Institute
1300 Wilson Boulevard
Arlington, VA 22209

1 Dr. Stanley L. Cohen
Work Unit Area Leader
Organizational Development
Work Unit
Army Research Institute
for the Behavioral and
Social Sciences
1300 Wilson Boulevard
Arlington, VA 22209

1 Dr. Leon H. Nawrocki
U. S. Army Research Institute
Rosslyn Commonwealth Building
1300 Wilson Boulevard
Arlington, VA 22209

1 Dr. Martin Rockway
Technical Training Division
Lowry Air Force Base
Denver, CO 80230

1 Maj. P. J. DeLeo
Instructional Technology Branch
AF Human Resources Laboratory
Lowry AFB, CO 80230

1 Headquarters, U.S. Air Force
Chief, Personnel Research
and Analysis Division
(AF/DPSY)
Washington, DC 20330

1 Research and Analysis Division
AF/DPXYR Room 4C200
Washington, DC 20330

1 AFHRL/AS (Dr. G. A. Eckstrand
Wright-Patterson Air Force Base
Ohio 45433

1 AFHRL (AST/Dr. Ross L. Morgan
Wright Patterson Air Force Base)
Ohio 45433

1 AFHRL/MD
701 Prince Street
Room 200
Alexandria, VA 22314

1 AFOSR(NL)
1400 Wilson Boulevard
Arlington, VA 22209

1 Commandant
USAF School of Aerospace
Medicine
Aeromedical Library (SUL-4)
Brooks AFB, TX 78235

1 CAPT Jack Thorpe, USAF
Department of Psychology
Bowling Green State University
Bowling Green, OH 43403

1 Headquarters Electronic
Systems Division
ATTN: Dr. Sylvia R. Mayer/MCIT
LG Hanscom Field
Bedford, MA 01730

1 Commandant, Marine Corps
Code AO1M-2
Washington, D.C. 20380

1 COL George Caridakis
Director, Office of
Manpower Utilization
Headquarters, Mareine Corps
(A01H), MCB
Quantico, VA 22134

1 Dr. A. K. Slafkosky
Scientific Advisor (Code Ax)
Commandant of the Marine Corps
Washington, DC 20380

1 Mr. E. A. Dover
Manpower Measurement Unit
(Code AOIM-2)
Arlington Annex, Room 2413
Arlington, VA 20370

1 Mr. Joseph J. Cowan, Chief
Psychological Research
Branch (P-1)
U. S. Coast Guard Headquarters
400 Seventh Street, SW
Washington, DC 20590

1 Dr. John Ford, Jr.
Navy Personnel Research
and Development Center
San Diego, CA 92152

1 LCDR Charles Theisen, Jr.,
MSC, USN, 4024
Naval Air Development Center
Warminster, PA 18974

1 Mr. Helga Yeich, Director
Program Management, Defense
Advanced Research
Projects Agency
1400 Wilson Boulevard
Arlington, VA 22209

1 Mr. William J. Stormer
DOD Computer Institute
Washington Navy Yard
Building 175
Washington, DC 20374

1 Dr. Ralph R. Canter
Director for Manpower Research
Office of Secretary of Defense
The Pentagon, Room 3C980
Washington, DC 20301

1 Office of Computer Information
Institute for Computer Sciences
and Technology
National Bureau of Standards
Washington, DC 20234

1 Dr. Eric McWilliams
Program Manager
Technology and Systems, TIE
National Science Foundation
Washington, DC 20550

1 Dr. Scarvia Anderson
Executive Director for Special Development
Educational Testing Service
Princeton, NJ 08540

1 Dr. Richard C. Atkinson
Stanford University
Department of Psychology
Stanford, CA 94305

1 Dr. Bernard M. Bass
University of Rochester
Management Research Center
Rochester, NY 14627

1 Mr. Edmund C. Berkeley
Berkeley Enterprises, Inc.
815 Washington Street
Newtonville, MA 02160

1 Dr. David G. Bowers
University of Michigan
Institute for Social Research
P. O. Box 1248
Ann Arbor, Michigan 48106

1 Dr. Ronald P. Carver
American Institutes for Research
8555 Sixteenth Street
Silver Spring, MD 20910

1 Century Research Corporation
4113 Lee Highway
Arlington, VA 22207

1 Dr. Robert Glaser, Director
University of Pittsburgh
Learning Research and Development Center
Pittsburgh, PA 15213

1 Dr. Kenneth B. Clark
University of Rochester
College of Arts and Sciences
River Campus Station
Rochester, NY 14627

1 Dr. Rene' V. Dawis
University of Minnesota
Department of Psychology
Minneapolis, MN 55455

2 ERIC
Processing and Reference Facility
4833 Rugby Avenue
Bethesda, MD 20014

1 Dr. Victor Fields
Department of Psychology
Montgomery College
Rockville, MD 20850

1 Mr. H. Dean Brown
Stanford Research Institute
333 Ravenswood Avenue
Menlo Park, CA 94025

1 Mr. Michael W. Brown
Operations Research, Inc.
1400 Spring Street
Silver Spring, MD 20910

1 Dr. Edwin A. Fleishman
American Institutes for Research
8555 Sixteenth Street
Silver Spring, MD 20910

1 Dr. Albert S. Glickman
American Institutes for Research
8555 Sixteenth Street
Silver Spring, MD 20910

1 Dr. Duncan N. Hansen
Florida State University
Center for Computer-Assisted Instruction
Tallahassee, FL 32306

1 Dr. Henry J. Hamburger
University of California
School of Social Sciences
Irvine, CA 92664

1 Dr. Richard S. Hatch
Decision Systems Associates Inc.
11428 Rockville Pike
Rockville, MD 20852

1 Dr. M. D. Havron
Human Sciences Research, Inc.
Westgate Industrial Park
7710 Old Springhouse Road
McLean, VA 22101

1 Human Resources Research Organization
Division #3
P. O. Box 5787
Presidio of Monterey, CA 93940

1 Human Resources Research Organization
Division #4, Infantry
P. O. Box 2086
Fort Benning, GA 31905

1 Human Resources Research Organization
Division #5, Air Defense
P. O. Box 6057
Fort Bliss, TX 79916

1 Human Resources Research Organization
Division #6, Library
P. O. Box 428
Fort Rucker, AL 36360

1 Dr. Lawrence B. Johnson
Lawrence Johnson and Associates, Inc.
200 S Street, NW, Suite 502
Washington, DC 20009

1 Dr. Norman J. Johnson
Carnegie-Mellon University
Graduate School of Industrial Admin.
Pittsburgh, PA 15213

1 Dr. David Klahr
Carnegie-Mellon University
Graduate School of Industrial Admin.
Pittsburgh, PA 15213

1 Dr. Robert R. Mackie
Human Factors Research, Inc.
6780 Cortona Drive
Santa Barbara Research Park
Goleta, CA 93017

1 Dr. Andrew R. Molnar
Technological Innovations in Education
National Science Foundation
Washington, DC 20550

1 Dr. Leo Munday
Vice President
American College Testing Program
P.O. Box 168
Iowa City, IA 52240

1 Dr. Donald A. Norman
University of California, San Diego
Center for Human Information Processing
La Jolla, CA 92037

1 Mr. Luigi Petrullo
2431 North Edgewood Street
Arlington, VA 22207

1 Dr. Robert D. Pritchard
Assistant Professor of Psychology
Purdue University
Lafaytte, IN 47907

1 Dr. Diane M. Ramsey-Klee
R-K Research & System Design
3947 Ridgemont Drive
Malibu, CA 90265

1 Dr. Joseph W. Rigney
Behavioral Technology
Laboratories
University of Southern
California
3717 South Grand
Los Angeles, CA 90007

1 Dr. Leonard L. Rosenbaum, Chairman
Department of Psychology
Montgomery College
Rockville, MD 20850

1 Dr. George E. Rowland
Rowland and Company, Inc.
P. O. Box 61
Haddonfield, NJ 08033

1 Dr. Arthur I. Siegel
Applied Psychological
Services and Science Center
404 East Lancaster Avenue
Wayne, PA 19087

1 Mr. Dennis J. Sullivan
725 Benson Way
Thousand Oaks, CA 91360

1 Mr. Dexter Fletcher
Department of Psychology
University of Illinois
at Chicago Circle
Box 4348
Chicago, IL 60680

1 Dr. Benton J. Underwood
Northwestern University
Department of Psychology
Evanston, IL 60201

1 Dr. David J. Weiss
University of Minnesota
Department of Psychology
Minneapolis, MN 55455

1
Denver Research Institute
University of Denver
Denver, CO 80210

1 Dr. Kenneth Wexler
University of California
School of Social Sciences
Irvine, CA 92664

1 Dr. John Annett
The Open University
Milton Keynes
Buckinghamshire
ENGLAND

1 Dr. Milton S. Katz
MITRE Corporation
Westgate Research Center
McLean, VA 22101

1 Dr. Charles A. Ullmann
Director, Behavioral
Sciences Studies
Information Concepts
Incorporated
1701 No. Ft. Myer Drive
Arlington, VA 22209

1 Dr. Anita West
Denver Research Institute
University of Denver
Denver, CO 802]0